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(60) Provisional application No. 61/433,966, filed on Jan. 18, 2011.

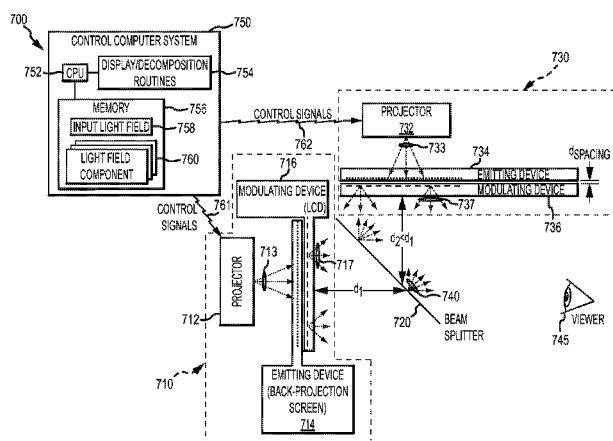
(51) **Int. Cl.**  
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(57) **ABSTRACT**

A multi-planar plenoptic display assembly with multiple spatially-varying light emitting and modulating planes. The display assembly includes at least one light emitting device and may include a modulating device used in conjunction according to display methods taught herein to display light field data. A display assembly controller may be used to render a light field with depth into a multi-planar plenoptic display assembly by assigning decomposed portions of the light field to the display assembly for display or presentation by differing ones of the emitting elements and by operating a modulating device to provide a parallax barrier. In one embodiment, a projector is used with bi-state screens. In another embodiment, two automultiscopic displays (either parallax barrier or lenticular lenses) are overlaid with a beam splitter. In a further embodiment, an oscillating mirror is used to temporally and optically move one automultiscopic layer (either parallax barrier or lenses) through space.

**19 Claims, 10 Drawing Sheets**



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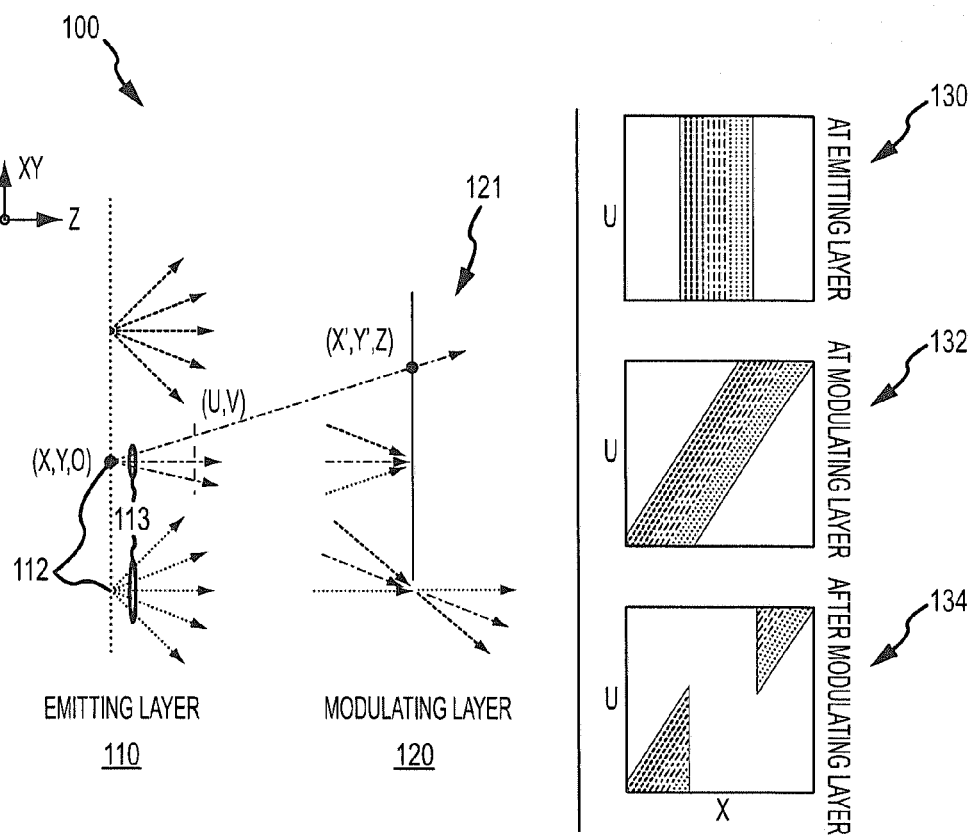


FIG.1

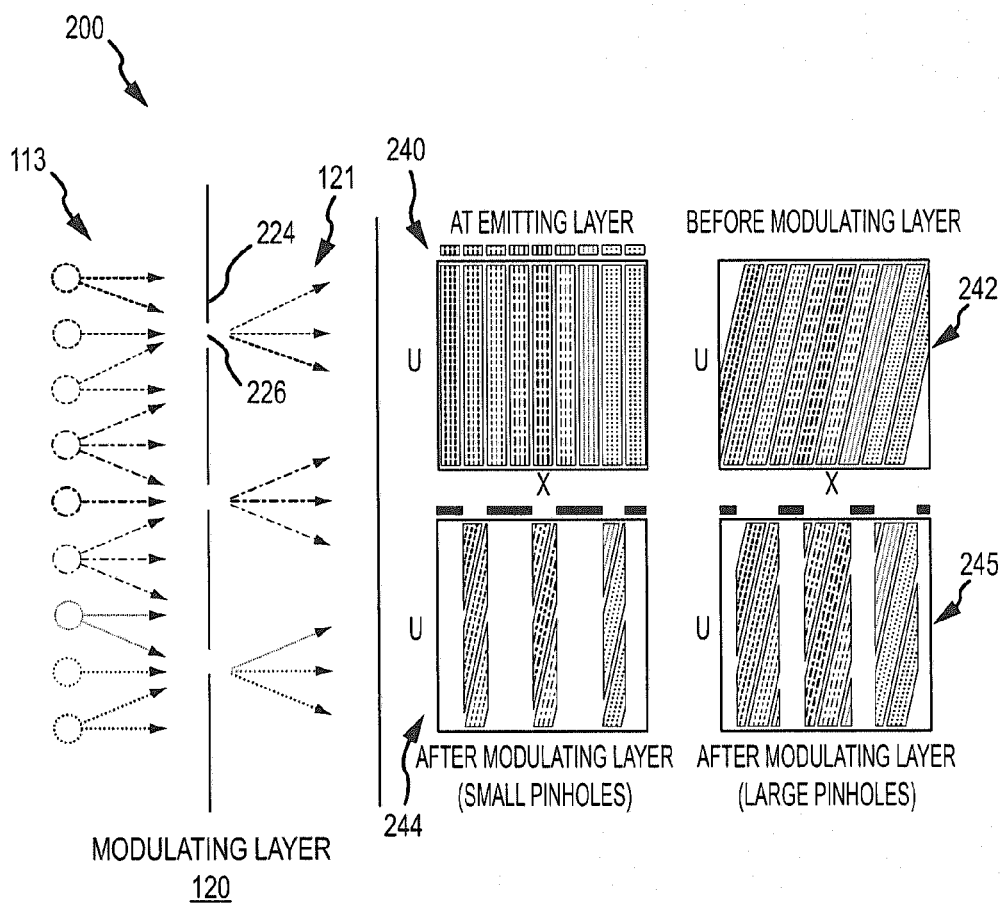


FIG.2

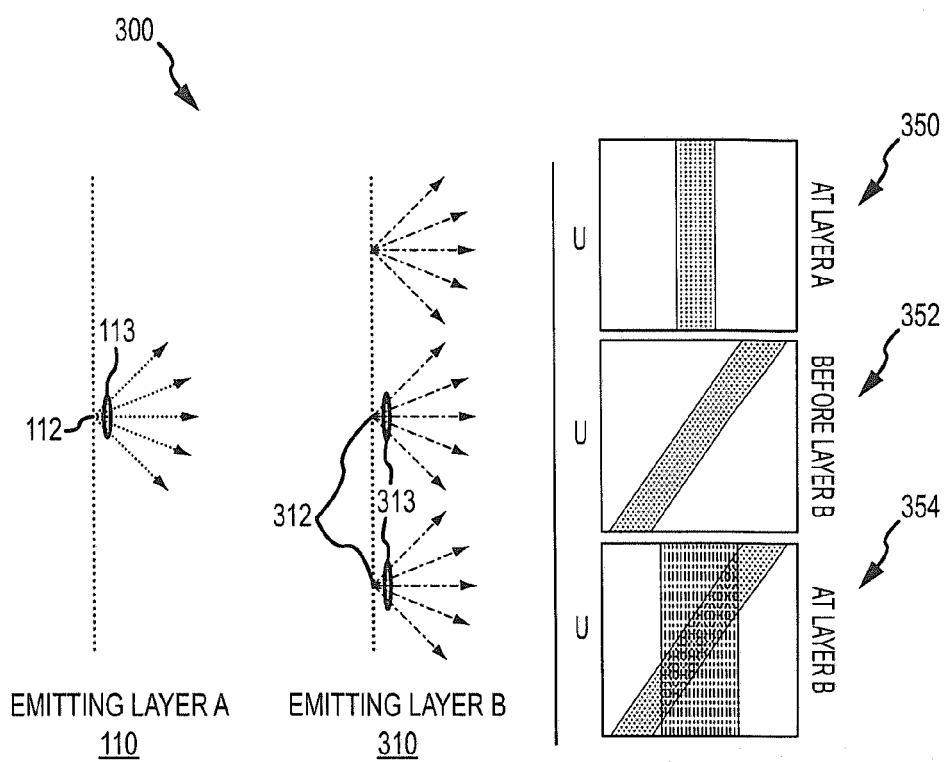


FIG.3

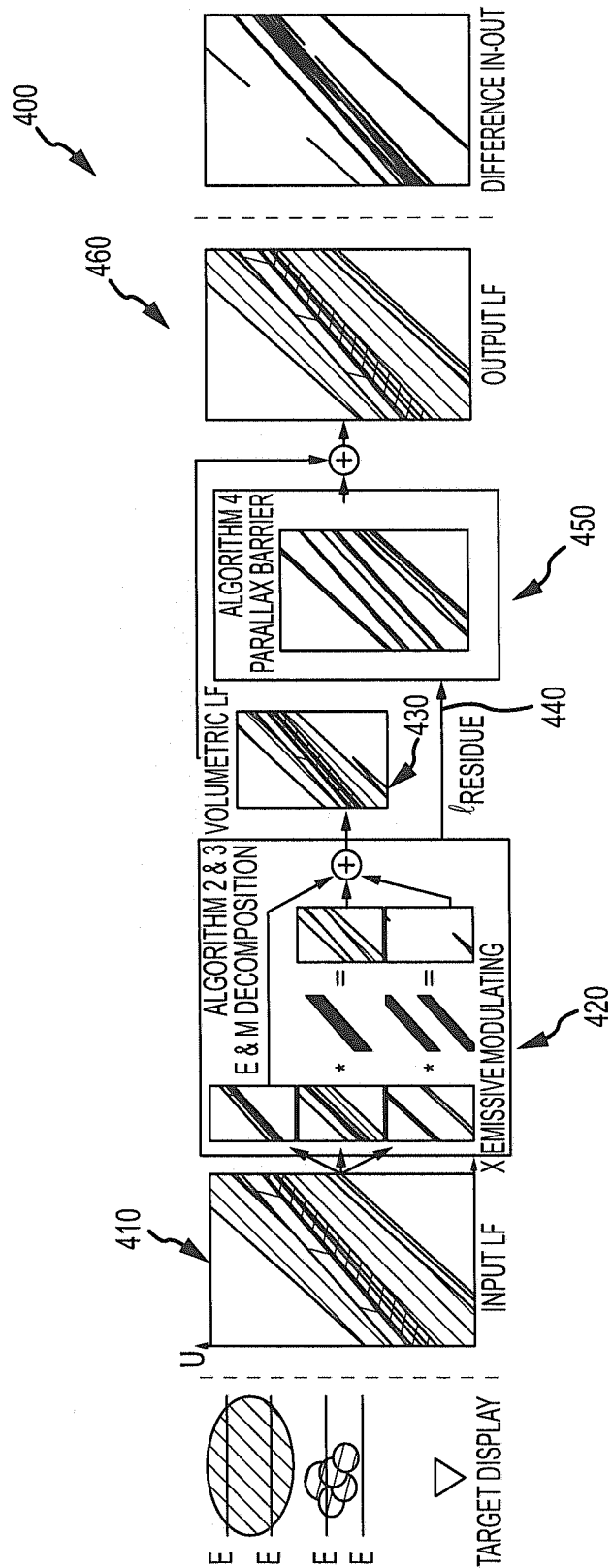


FIG.4

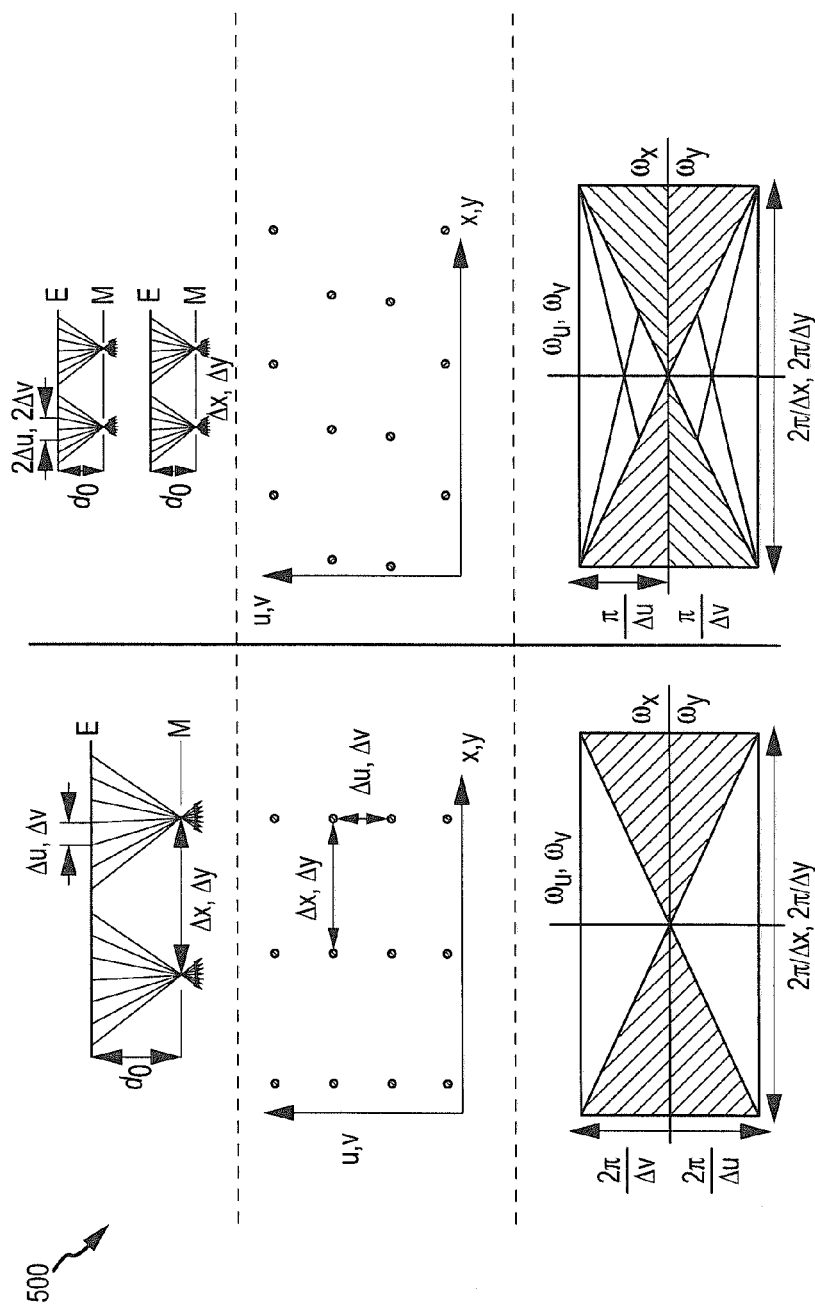


FIG. 5

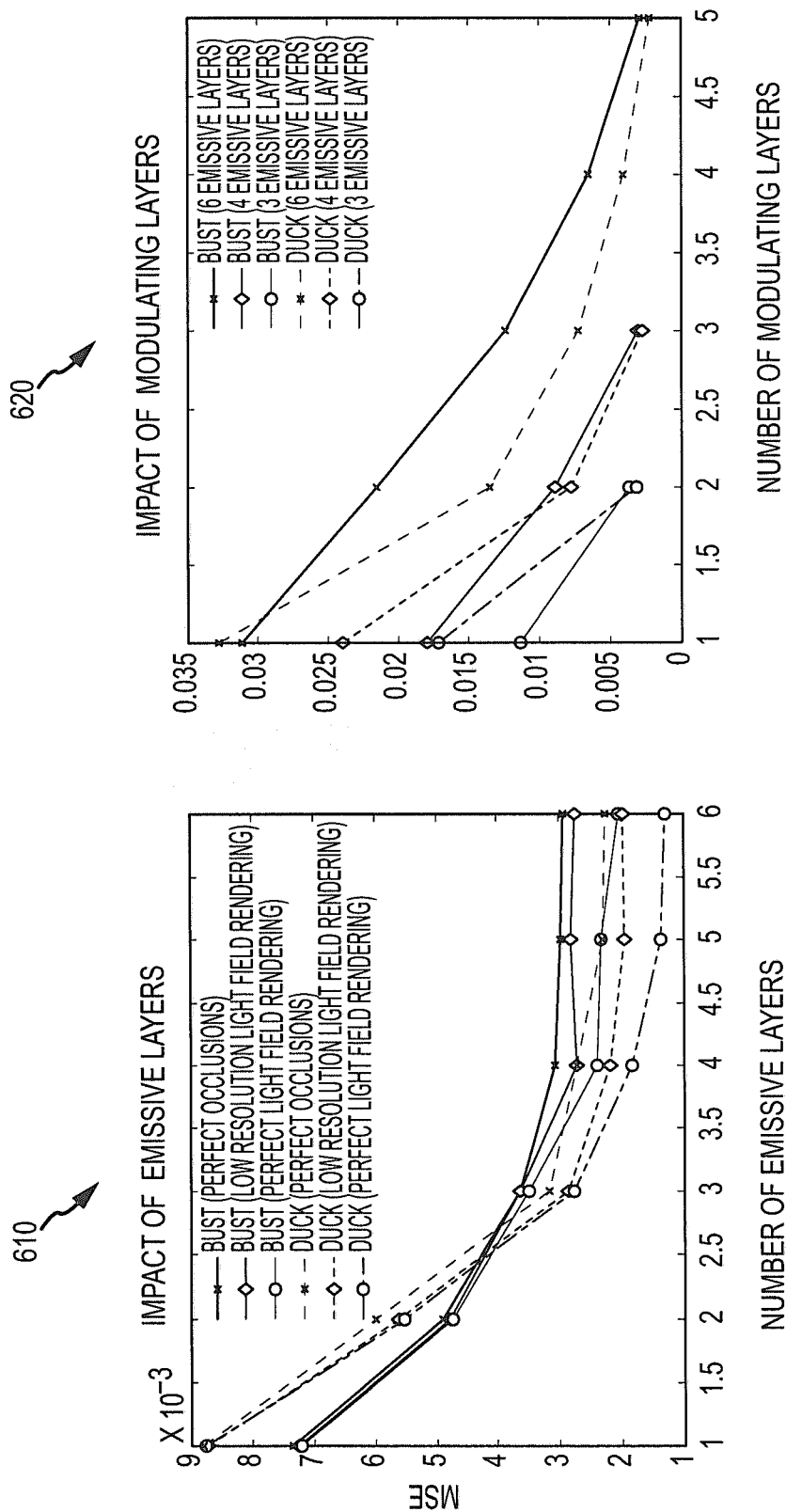


FIG.6



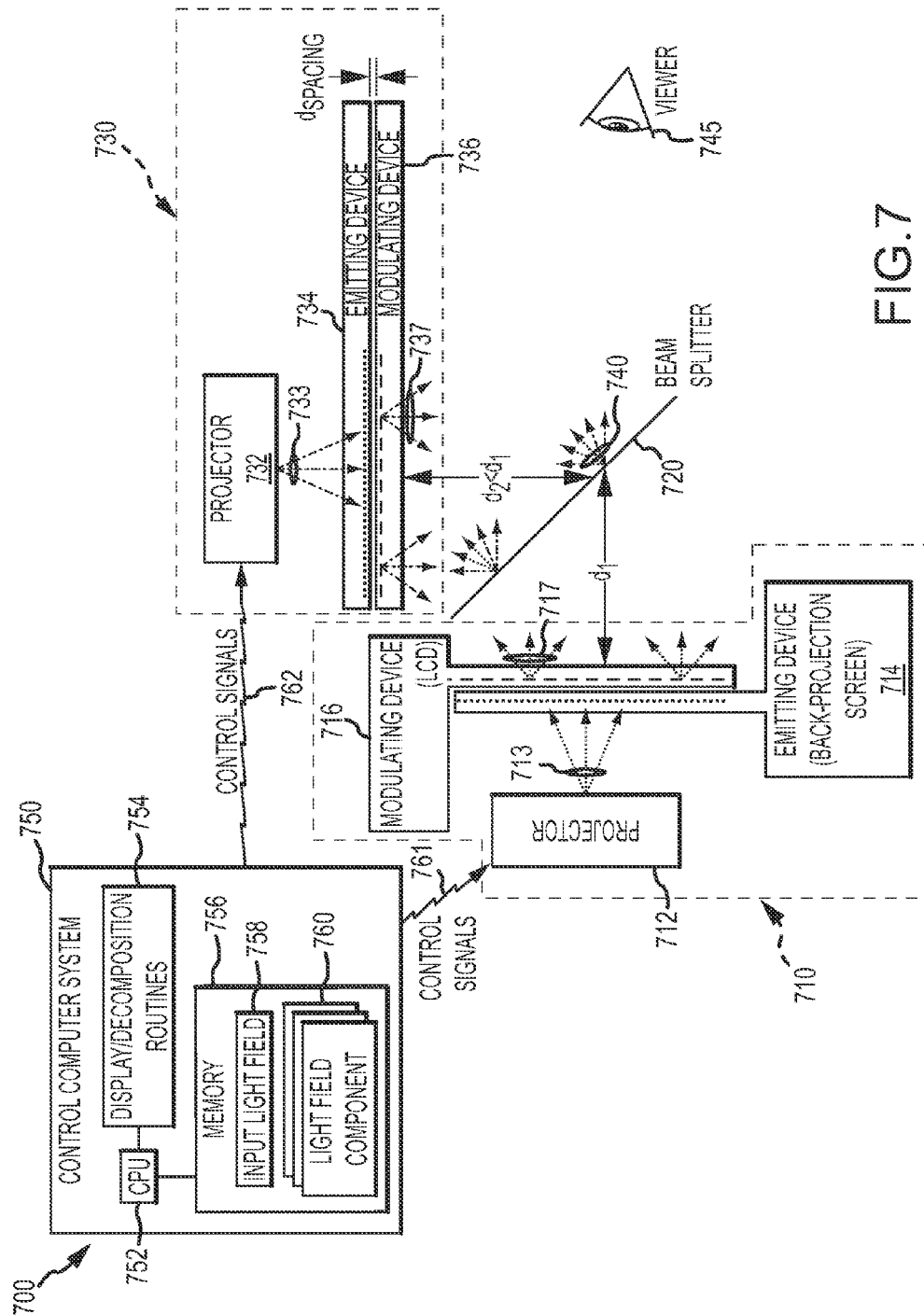


FIG. 7

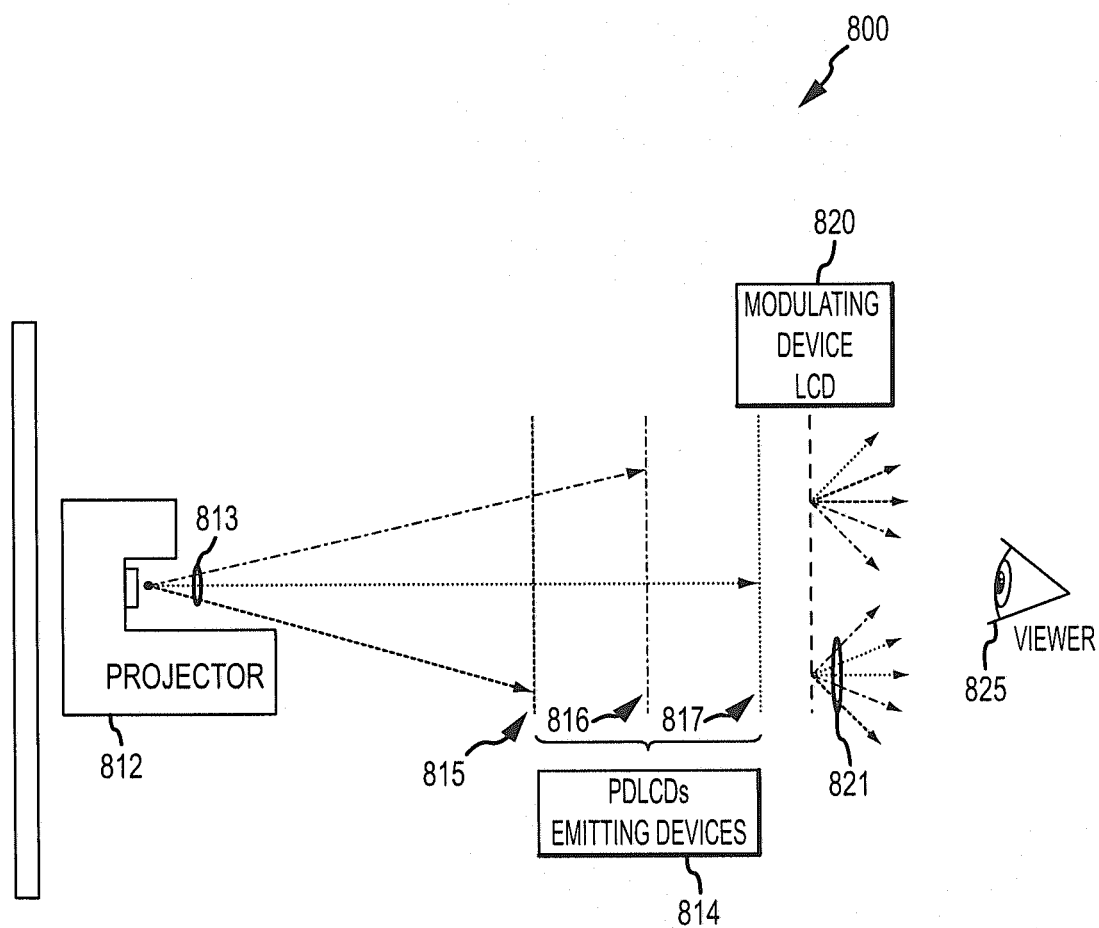
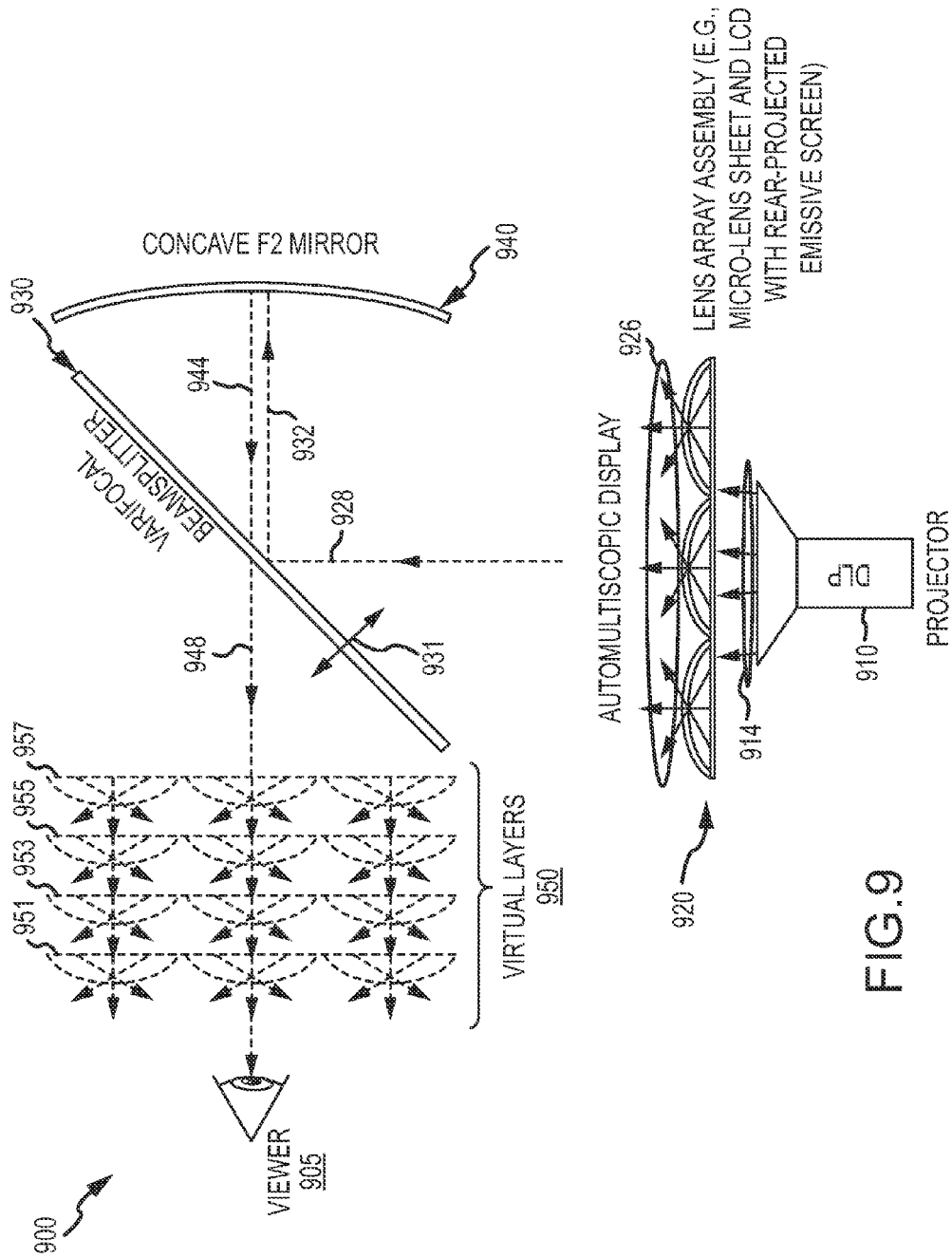


FIG.8



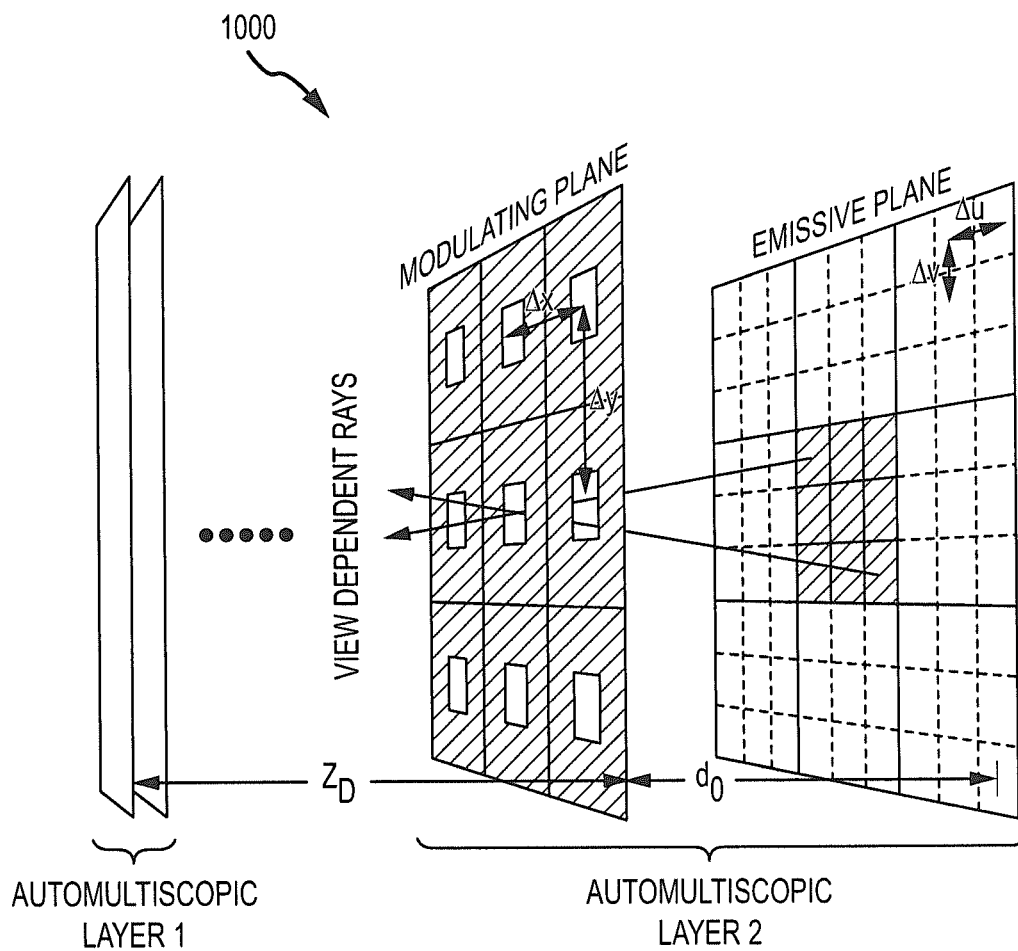


FIG.10

# MULTI-LAYER PLENOPTIC DISPLAYS THAT COMBINE MULTIPLE EMISSIVE AND LIGHT MODULATING PLANES

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 13/184,693, filed Jul. 18, 2011, issued as U.S. Pat. No. 8,643,684, which claims the benefit of U.S. Provisional Application No. 61/433,966, filed Jan. 18, 2011, both of which are incorporated herein by reference in their entireties.

## BACKGROUND

### 1. Field of the Description

The present description relates, in general, to automultiscopic display methods and devices (e.g., methods and devices for creating differing views in differing directions without regard of eye position and without need for head-mounted gear to view a three-dimensional (3D) effect), and, more particularly, to multi-layer plenoptic displays that combine multiple emissive and light modulating planes that are adapted to provide increases in depth range and resolution when compared to both parallax barrier displays and volumetric displays.

### 2. Relevant Background

Displays that provide the illusion of three dimensions (3D) have become increasingly popular in many entertainment settings from movie theaters to venues such as amusement parks, shopping malls, and the like to home viewing with advances in televisions, computer monitors, and video game systems. The trend toward 3D display devices is likely to continue and is being driven in part by the increasing amount of 3D content available for movies, television, and video games.

While the majority of 3D displays currently require that the audience or viewers wear special glasses, there has recently been significant research toward autostereoscopic and automultiscopic displays. In automultiscopic display systems, techniques are used to display 3D images that can be viewed without the use of special headgear or glasses. It is generally agreed within the entertainment industry that automultiscopic displays unencumbered by glasses offer significant advantages over other 3D displays. Technological progress has been made in providing automultiscopic displays with improved resolution and user-perceived quality, and such progress may soon lead to more widespread adoption of automultiscopic displays as long as issues with occlusion and limitations on user viewing positions can also be addressed.

In general, parallax-based displays and volumetric displays are the two main types of 3D displays that currently are used to provide an automultiscopic experience. Parallax-based displays typically include a parallax barrier and employ horizontally modulated blocking patterns to provide different viewer rays for different viewing angles. A parallax barrier is a device that may be placed in front of an image source, such as a liquid crystal display (LCD) or the like, to allow the image source to show or display a stereoscopic or 3D image without the need for the viewer to wear 3D glasses. The parallax barrier may include a layer of material with a series of precision slits that allow each eye of a viewer to see a different set of pixels, and this creates a sense of depth through parallax in an effect that is similar to 3D images viewed with lenticular devices used with printed interlaced images. Volumetric displays provide images of 3D objects

with correct focus and depth cues by creating a volume of individually controlled light sources, which is in contrast to the multiplexing of light rays for differing viewing directions done in parallax-based displays.

Unfortunately, both parallax-based and volumetric displays have disadvantages that have limited their use and more widespread adoption to display 3D content. Parallax-based displays typically require an extremely large display resolution to satisfy the depth range of most 3D scenes and to avoid aliasing artifacts. Further, the effective horizontal pixel count viewable by each eye is reduced by one half.

Volumetric displays typically operate by superimposing translucent light emitters, and, as a result, a key disadvantage with volumetric displays is that they cannot represent occlusion or view-dependent effects (e.g., a viewer can often see objects behind a displayed foreground image instead of the foreground image occluding or blocking the object from view). In conventional volumetric displays, all voxels that are occluded by other voxels in an input 3D model are merged such that there are no mechanisms to block the light and provide proper occlusion.

Some occlusion-capable displays have been designed that have been labeled volumetric by some in the industry. However, these displays are useful quite similar to parallax barrier-based displays. For example, instead of using blocking patterns to provide different viewing rays for different viewing angles, such displays may employ time multiplexing with a high-speed projector and a rotating vertical anisotropic mirror to attain the same effect. As a result of this design, such displays suffer from the same problem as the parallax barrier-based display in that their working volume is limited by the angular resolution, e.g., the number of images displayed during one revolution of the mirror. In addition, physically scaling the design poses significant mechanical challenges. Other “volumetric displays” attempting to provide a truer autostereoscopic display also have issues limiting their adoption. For example, one such system uses two volumetric displays and a set of beamsplitters to direct the light from each display to the correct eye, but this system only displays two fixed viewpoints.

Hence, there remains a need for improved 3D displays (or display systems) and automultiscopy display methods that can better handle occlusions and other issues limiting use of such displays such as limited number of viewers/viewpoints, specific and tight viewer positioning requirements, and aliasing artifacts.

## SUMMARY

The present invention addresses the above problems by providing multi-planar plenoptic display assemblies/systems (or displays) that include multiple spatially-varying light emitting and light modulating planes. In other words, the display assemblies described include at least one emitter element or device and at least one modulator element or device that can be used in conjunction according to display methods taught herein to display light field data on this new type of display assembly.

To assist in understanding the described concepts, the following description includes a mathematical notation describing each of the layers (provided by each light emitting and light modulating element/device) in terms of the corresponding light transport operators. The inventors have created a process that may be carried out by software (e.g., run within a display assembly controller or by a computer system used to first generate content/control programs for the display assembly), and this process (or algorithm) renders a light field with

depth into a multi-planar plenoptic display assembly (e.g., assigns portions of the light field to the display assembly for display or presentation by differing ones of the display elements such as by a modulator used to provide a parallax barrier or by emitting on an emissive display element used to display a particular layer of the 3D content or light field).

The following description also provides an analysis of the bandwidth of a multi-planar plenoptic display assembly. This bandwidth is then compared (favorably) with the bandwidth of traditional parallax barriers. The results of simulations for different display configurations are also presented in the following description. Numerous implementations of multi-layer plenoptic display assemblies may be utilized to practice the ideas and display methods taught herein, and, with this in mind, the description includes two different embodiments of useful display assemblies that have been successfully prototyped by the inventors. The first design uses a dynamic parallax barrier (e.g., a modulator plane or modulating element in the form of a liquid crystal display (LCD)) and a number of bi-state (transparent/translucent) screens (e.g., 2 to 3 or more emitting elements or emitter plane devices such as polymer-dispersed LCDs or (PDLCDs)). The second design uses a beam splitter to co-locate one or two pairs of automultiscopic displays, a parallax barrier (the modulator plane), and a static rear projector screen (e.g., the emitter plane). In some implementations of this second design, two automultiscopic displays may be collocated in the setup. A projector-diffuser pair is one example of such an automultiscopic display, with other examples including two LCDs stacked together to form an automultiscopic display. Both designs were evaluated on a number of differing 3D scenes/content, and the advantages and disadvantages of each design are presented.

More particularly, an automultiscopic display apparatus is provided that includes a planar light modulating device, such as an LCD, that is selectively operable to display parallax barrier patterns (e.g., occluded portions of view-dependent components of a light field). The display apparatus also includes first and second planar emitting devices each selectively operable to emit received light, and these may also be LCDs (such as PDLCDs) such that they are arrays of point light sources. In practice, three or more PDLCDs may be utilized (with more being possible/useful with a high speed projector), and the number of such planar emitting devices is generally only limited by the actual hardware employed. The display apparatus also includes a controller (or computer with decomposition/display software) operating the first and second emitting devices to display first and second components of a light field and operating the modulating device to occlude a portion of the light field.

In some embodiments of the display apparatus, the first and second components both include view independent components that were extracted from the light field. The first and second emitting devices are typically positioned to display the first and second components in spaced apart planes (e.g., stacked in a parallel manner behind the modulating device or at differing distances from a beam splitter). The first component of the light field may include view-dependent components extracted from the light field and the parallax barrier pattern may be generated to mask view-dependent occlusions in the light field, whereby portions of the first component are blocked by the modulating device. In practice, the modulating device may be configured to be opaque or transparent at an array of spatial positions to display the parallax barrier pattern, e.g., be an LCD monitor selectively operable or pro-

grammable by the controller to display one or more parallax barrier patterns to occlude portions of the light field.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates graphically light transport in a portion of a multi-layer plenoptic display assembly of the present description;

FIG. 2 illustrates graphically light transport in the modulating layer of a multi-layer plenoptic display assembly (or parallax barrier display);

FIG. 3 illustrates graphically light transport in a display assembly with two emitter layers (or emitting devices) stacked in parallel;

FIG. 4 illustrates an exemplary display (or decomposition) method for use with a display assembly of the present invention;

FIG. 5 illustrates graphically a bandwidth analysis for multiple layers of a parallax barrier-type display assembly;

FIG. 6 illustrates error plots for emissive layers and for modulating/blocking layers in a display assembly;

FIG. 7 illustrates schematically or in functional block form a multi-layer display assembly of one embodiment using spatial multiplexing and including two auto-multiscopic parallax barrier displays (note, though, the assembly is not limited to use of a projector/LCD combination as it may include or utilize an LCD/LCD combination (one being used for emission and one for modulation) or any automultiscopic display);

FIG. 8 illustrates another multi-layer display assembly using temporal multiplexing and including multiple emitting devices and a single modulating device;

FIG. 9 illustrates a multi-layer display assembly using a lenticular lens array to provide temporally multiplexed automultiscopic displays and a varifocal beam splitter to provide the automultiscopic displays to a viewer as virtual display layers at different, spaced apart locations or planes in the viewing space; and

FIG. 10 illustrates a schematic diagram of a dual-layer display assembly.

#### DETAILED DESCRIPTION

Briefly, the following description is directed toward multi-planar plenoptic displays and autostereoscopic display methods making use of such displays. These displays or display assemblies uniquely combine elements of both parallax barrier displays and volumetric displays to achieve a surprisingly better display of 3D content. In general, the multi-planar plenoptic display assemblies include multiple display elements that are used to provide two or more planes including at least one light emitting plane and at least one light modulating plane. The display assemblies utilize these display elements to alleviate common problems present in both parallax barrier-type displays and volumetric-type displays. In particular, the display assemblies taught and described herein are operable to represent volumetric (or 3D) content with proper occlusion between different elements or objects within a 3D scene. Moreover, the display assemblies may be designed and operated to increase the available depth range, which had limited use and effectiveness of typical parallax barrier-type displays.

The design space for multi-planar plenoptic display assemblies of the present description is large since there are many possible ways to arrange and combine the differing components (e.g., the emitter plane device(s) and the modulator plane device(s)). Therefore, to better explain the significant

concepts taught by the inventors, the description below begins with a mathematical framework that describes light transport for different display elements and their various combinations. Then, given a particular light field, scene depth, and display assembly configuration, the description explains how the display method (or a display assembly's components such as software programs) includes steps to decompose the input light field (or 3D content file) into components (or light field portions, segments, subsets, or the like) that each can be separately rendered or displayed/presented by different ones of the display layers or display elements of the multi-layer plenoptic display assembly. In other words, a controller of the display assembly functions to synchronize operation of each of the separate display elements to selectively display a portion or subset of the light field.

Further, the following description provides an analysis of the available bandwidth of the multi-planar plenoptic displays, which shows that their bandwidth increases linearly with the number of display elements. The inventors describe simulations of different configurations of multi-planar plenoptic display assemblies, and this includes providing an error analysis with respect to the input data. Two prototypes or useful embodiments of display assemblies are then described with reference to the figures.

The first embodiment of a display assembly uses a single dynamic parallax barrier (e.g., a modulator or modulating element operated by the controller as a changeable parallax barrier), a stack of bi-state translucent shutter glass (e.g., two or more emitters or emitting elements), and a projector projecting on these emitters. Each sheet of the shutter glass can act as (and be controlled as) a separate spatially-varying, light-emitting plane (or emitting element). This first embodiment can render volumetric or 3D content with proper occlusion processing and view-dependent shading and specularities. The second embodiment of a display assembly uses interleaved, dynamic parallax barriers and static diffusers, and this second design is capable of displaying a scene with a large depth range.

Briefly, the reader of this description should readily be able to identify several innovative steps or contributions provided by the inventors. First, the inventors teach design and use of multi-planar plenoptic displays as well as a mathematical framework to analyze light transport by such displays. Second, the inventors teach an algorithm or computer-implemented method to decompose an input light field (or input light field data set) into components (e.g., light field portions or subsets of the light field data set) and further teach an algorithm or computer-implemented method to render these components on a multi-planar or multi-layer plenoptic display. Third, the inventors provide a bandwidth analysis for multi-planar plenoptic displays. Fourth, the inventors describe an analysis of different layer/plane display element configurations as well as the respective error compared to the ground truth data. Fifth, the inventors teach two specific and differing physical implementations or embodiments of multi-planar plenoptic display assemblies that have been proven to extend depth range and to render volumetric or 3D content with proper occlusion and view-dependent shading and specularities.

The display assemblies described may each be thought of as a hybrid multi-layer plenoptic display that includes multiple layers of autostereoscopic and volumetric display primitives (e.g., display elements). A "primitive" may be operated to either emit incoming light (e.g., from a projector providing 3D content or a light field) or modulate the incoming light. The mathematical framework for light emission, modulation, and transport for a given layer/planar configuration of the

display elements or primitives is described below. A process or algorithm is presented that can be used to decompose or divide an input light field (e.g., content that describes or provides a 3D scene) into an approximated output light field, which can then be directly mapped onto the different display elements/primitives of a given multi-layer display assembly. The decomposition process/algorithm may then be analyzed as discussed below in terms of resulting bandwidth and approximation errors.

The inventors validated their decomposition algorithm and their display simulations by using two different display assembly prototypes. The first setup/prototype used a stack of emitting primitives combined with one modulating primitive. The second display setup uses two parallax barrier primitives that are virtually stacked onto each other (e.g., via a beam splitter). The following description further includes an analysis of the results of these two prototypes/setups for a variety of input light fields and also includes a discussion of possible limitations of these displays and possible modifications to address such limitations.

Before turning to particular implementations for display assemblies, it may be useful to define a model or mathematically analyze multi-layer plenoptic displays. This analysis can then be used to assemble various display assemblies from a small set of primitives (display elements) in order to achieve higher resolution and greater apparent depth than achieved with prior autostereoscopic systems. The analysis of the multi-layer display assembly is based on emission, transport, and modulation of the light field. In general, the light field,  $l$ , describes radiance of light rays passing through points  $(x,y)$  and  $(u,v)$  at a distance,  $z$ , from the  $xy$  plane, and the light field may be denoted as  $l(x,y,z,u,v)$ . For ease of explanation, the following analysis only considers light rays traveling along the positive  $z$  direction, as the display assemblies will typically only be viewed from the front when in use.

FIG. 1 illustrates with a graph 100 the basic light transport in a display that includes an emitting layer 110 and a modulating layer 120. The graph 100 shows that the emitting layer (emitter or emitting device) 110 includes an array of point light sources 112 emitting light 113 toward an inner or back side of a modulating layer (modulator or modulating device) 120, which includes an array of optical elements that can either be opaque/translucent or substantially transparent to transmit light 121 outward from the display assembly to a viewer (not shown). Graphs 130, 132, 134 show the light field after the emitting layer 110, received at the modulating layer 120, and after the modulating layer 120, respectively.

Each ray is parameterized by  $(x,y)$ ,  $z$ , and  $(u,v)$ . As the ray moves in space, its  $(x',y',z)$  position changes by shear, but its angle is constant. Emitting layers, such as layer/emitting device 110, act as an array of point light sources 112 and are constant across all angles. Modulating layers, such as layer/modulating device 120, are also constant in angle and can be dynamically or selectively made to be opaque at each spatial position (or at each optical element) to create a plurality of transmissive openings or "pinholes" (as shown in FIG. 2) that transmit light 121 to a viewer observing or using the display assembly. The basic light transport is illustrated in FIG. 1. A ray starting at position  $(x,y)$  passing through  $(u,v)$  traverses in free space to position  $x'=x+zu$ ,  $y'=y+zv$ . As the ray moves in depth, its position will change to  $(x',y',z)$  while keeping its original traveling direction.

FIG. 2 illustrates with a graph 200 further details of basic light transport in a display with particular emphasis on the modulating layer 120. The graph 200 shows the modulating layer receiving light 113 from an emitting layer or plane. The modulating layer or modulating device 120 is controlled to

provide a parallax barrier with its spatial positions or optical elements operated to selectively be opaque to provide barriers/blocks **224** to light **113** and other ones of the spatial positions or optical elements operated to be transparent/translucent to provide pinholes/openings **226** through which light **121** is transmitted on to a viewer. This case describes the principle of autostereoscopic and automultiscopic displays using parallax barriers for multiplexing different images into different views, but, it will be understood, this is only one exemplary or special case of this particular setup or tested arrangement.

The light field **113** is shown graphically at **240**, **242**, **244**, and **245** as it may appear at the emitting layer **110**, before the modulating layer **120**, and after the modulating layer **120** with small and large pinholes **226**, respectively. As shown, a parallax barrier provided by the barriers/blocks and holes **224**, **226** of the modulating layer **120** allocates the spatial variation of the emitter **110** into spatial and angular variation. Increasing the size of the pinholes **226** increases the display brightness, but it also causes visible crosstalk, as can be seen in the upper left and lower right corners of the three bars in the image **245**.

Any new display assembly can be constructed by stacking (or combining) multiple parallel planes (display elements) that either emit or spatially modulate light. In the notation used herein, all planes (display elements) are co-aligned with the x,y axes and are stacked along depth z. Each plane/display element/primitive modifies the rays passing through it relative to their x,y position but not in the u,v orientation. From FIGS. 1 and 2, it is clear that the emissive plane or primitive **110** (or E) acts like an array of point light sources **112** that each emit constant spherical waves. The notation  $E_z(x,y)$  may be used as the x and y values for the plane at depth z. The emissive plane **110** adds light to an input field,  $I_i$  (such as a light field from a projector) and yields an output light field,  $I_o$  (also shown at **113** in FIGS. 1 and 2), which may be represented as  $I_o(x,y,z,u,v) = I_i(x,y,z,u,v) + E_z(x,y)$ .

A spatial modulating plane, V (also known as the modulating element and labeled **120** in FIGS. 1 and 2), will partially attenuate certain rays **113**. The modulating layer,  $V_z(x,y)$ , is therefore represented as scalar between zero and one, and the output light field **121** can also be described or represented as  $I_o(x,y,z,u,v) = I_i(x,y,z,u,v) + V_z(x,y)$ .

With regard to a light field layer, a multiscopic parallax barrier layer device or assembly can be provided with the arrangement shown in FIGS. 1 and 2. In other words, a parallax barrier layer assembly or display uses one emissive layer (one emitting element such as element **110**) and one modulating layer (one modulating layer or element such as element **120**), and these two layers or display elements are separated by a small distance,  $\Delta z$ . Since this pairing is important to the display assemblies described herein, the light field layer (or multiscopic parallax barrier assembly) is considered a third primitive.

In the parallax barrier layer or assembly, the modulating layer is used to achieve ray separation by displaying a vertical slit pattern, while the emissive layer displays the different rays that pass through the slits. As a consequence, an observer will see different rays from different directions. In each emitter row, N pixels can be partitioned into any number of spatial, x, and angular, u, samples, such that N is greater than or equal to xu. In practice, such displays trade a substantial reduction of spatial resolution for a relatively small amount of rays and apparent depth.

FIG. 3 provides a graph **300** showing emitting layer superposition, and a display assembly may include two, side-by-side emitting layers **110**, **310**. Each provides an array of point

light sources **112**, **312** emitting light **113**, **313**. The light rays or light fields are shown at **350**, **352**, **354** at the first emitting layer **110**, before the second emitting layer **310**, and at the second emitting layer **310**, respectively. Two emitter planes **110**, **310** at different depths, as shown, allow for (or provide a display assembly with) more accurate light field rendering. This effect can be created in a display assembly using a beam splitter, temporal multiplexing with an electrically switchable scatterer, transparent OLEDs, or the like.

With regard to FIG. 3, the model for multi-layer plenoptic display assemblies combines multiple emitter and modulating planes (or emitting and modulating display elements) using a superposition onto the same optical path. Specifically, FIG. 3 illustrates with graph **300** that, using superpositioning, additional rays can be generated or can be partitioned into different angular resolution bins.

Based on the mathematical analysis in the above paragraphs with reference to FIGS. 1-3, an algorithm or method, which typically is carried out by software, can be described for displaying an input light field (or 3D content) in a particular/selected multi-layer plenoptic display assembly. Specifically, the display algorithm approximates an input light field,  $I_{IN}(x,y,u,v)$ , as an output light field,  $I_{OUT}(x,y,u,v)$ , that is targeted for a given or selected multi-layer plenoptic display assembly. The display algorithm/method decomposes the input light field into a number of components (field subsets/portions), and each component is then displayed on one or more of the display primitives (e.g., a controller operates the primitives or emitting and modulating display elements to selectively display the components produced by the decomposition of the input field). In order to aid the decomposition process/step, an assumption may be made that for all rays  $(x,y,u,v)$  of the input light field that the depth, z, is known for the closest object, the diffuse component  $R_D$ , and the specular/glossy component  $R_S$ .

More specifically, the display algorithm/method separates the light field data into planar components. First, the view-independent volumetric components,  $I_{IV}$ , are extracted from the light field, i.e.,  $I_{IV}$  will contain the rays that are not occluded at any angle. Second, a view-dependent, partially occluded volumetric part or component,  $I_{VDV}$ , is extracted from the light field data. Third, the remaining residue,  $I_{VDL}$ , is extracted for rendering with parallax barrier layers. Algorithm/method 1 below gives a high level overview of this display algorithm/method that is used to generate the output light field,  $I_{OUT}$ , from an input light field,  $I_{IN}$ , for a given display assembly,  $D_{IN}$ .

Algorithm 1: High level overview of the rendering algorithm.

---

```

 $I_{IV} \leftarrow \text{assignViewIndependentVolumetric}(I_{IN}, D_{IN})$ 
 $I_{residue} \leftarrow I_{IN} - I_{IV}$ 
 $I_{VDV} \leftarrow \text{assignViewDependentVolumetric}(I_{IN}, I_{residue}, D_{IN})$ 
 $I_{residue} \leftarrow I_{residue} - I_{VDV}$ 
 $I_{VDL} \leftarrow \text{assignViewDependentLightfield}(I_{residue}, D_{IN})$ 

```

---

FIG. 4 illustrates an exemplary display (or decomposition) method **400** that may be used for a display assembly made up of three emitting display elements (emissive layers), one modulating display element (modulating layer), and one parallax barrier element (parallax barrier layer)(in combination, shown as the layers "E"). The method **400** may be carried out by a processor(s) running a software program configured to carry out the steps of Algorithm/method 1 shown and described above. Specifically, an input light field (or light field data set) **410** is provided, and emissive and modulating decomposition is performed at **420** including assigning sepa-



rated components to the emissive and modulating layers, e.g., to provide a volumetric light field display as shown at **430** (with the emissive layers operated according to Algorithm 2 and the modulating layers operated according to Algorithm 3 discussed in Paragraphs [0046] and [0049]). The residual **440** from these decompositions is typically assigned or provided to the parallax barrier layer for rendering based on or after performance of Algorithm 4 described in Paragraph [0053]. In combination, the method **400** provides or displays the output light field **460**.

With regard to the emissive layers, in a first step of the method **400**, all diffuse components are extracted from the light field **410**. The extracted components, which may also be considered view-independent components, are then distributed onto the available emitting layers (or emitting display devices). Only extracted components that are spatially close enough to the emitting layers are considered for display. More specifically, each part of  $R_D$  (or the diffuse components) that is within a preset (but, user adjustable in many cases) distance or threshold distance,  $Z_{thresh}$ , from any emitting layer is assigned to the nearest emitting layer in the layered setup,  $D_{IN}$ . Assignment is performed by projection in some embodiments of the method **400**. The parts of the diffuse components  $R_D$  that are further than this threshold distance,  $Z_{thresh}$ , from all emitting layers are not processed and are left as residue **440** for the automultiscopic display layers. Algorithm 2 below summarizes this procedure of operating the emitting display devices or layers of the display assembly to display portions of an input light field (or 3D content).

Algorithm 2:

---

```

 $l_{VTI} \leftarrow \text{assignViewIndependentVolumetric}(l_{IN}, D_{IN})$ 
for emissiveLayer  $\in D_{IN}$ 
  for  $x, y, z, R_D \in l_{IN}$ 
     $dz \leftarrow \text{distance}([x, y, z], \text{emissiveLayer})$ 
    if  $R_D \neq 0$  and  $dz < Z_{thresh}$ 
      emissiveLayer[x,y]  $\leftarrow R_D$ 
       $l_{VTI}.add([x, y, z, R_D])$ 

```

---

Next, the display method **400** is adapted to consider view dependent components of the input light field **410**. After extracting the view-independent components, the remaining view-dependent light field parts need to be displayed on a combination of the emissive layers and the modulating layers of the multi-layer plenoptic display assembly. In the following discussion, an algorithm/method (a subroutine of the overall display method/algorithm (e.g., Algorithm 1)) is described that is capable of approximating proper occlusion using modulating layers as light blockers. Then, a step or subroutine for approximating the remaining residue using parallax barrier rendering is described.

In some display assemblies, a collection of modulating layers may be used to achieve volumetric rendering with occlusion. In the simplest and most straightforward case, multiple modulator-emitter pairs may be stacked to achieve direct proper occlusion. However, many light modulators, such as LCD panels, tend to absorb a substantial amount of light. Hence, it may be impractical to stack multiple modulating layers in sequence. Instead, view-dependent occlusions are approximated in some embodiments using fewer modulating layers (e.g., one to three layers or the like).

To this end, the display method may use Algorithm 3 to approximate proper occlusion. For every emissive ray, the algorithm/method (or software running a program implementing the method) identifies all occluders in the input light field,  $l_{IN}$  (also labeled **410** in FIG. 4). Then, all occluded rays

are masked by the closest modulating plane (or modulating display element of the display assembly), and all visible rays are distributed to the emissive layers (or emitting display elements of the display assembly), with these results/steps shown at **420** and **430** in FIG. 4. Also, see, Algorithm 3 below for more detail.

Algorithm 3:

---

```

 $l_{VDI} \leftarrow \text{assignViewDependentVolumetric}(l_{IN}, l_{residue}, D_{IN})$ 
for emissiveLayer  $\in D_{IN}$ 
  for  $x, y, z, R_D \in l_{residue}$ 
     $dz \leftarrow \text{distance}([x, y, z], \text{emissiveLayer})$ 
    if  $R_D \neq 0$  and  $dz < Z_{thresh}$ 
      emissiveLayer[x,y]  $\leftarrow R_D$ 
       $l_{VTI}.add([x, y, z, R_D])$ 
      for  $x', y', z', R_D' \in l_{IN}$ 
        if occludes( $[x', y', z'], [x, y, z]$ )
          modulator  $\leftarrow \text{getClosestModulator}([x', y', z'])$ 
          modulator[x',y'].occlude( )
      for modulator  $\in \text{Modulators}$ 
        for  $u, v \leftarrow \text{modulator.OccludedPixels}()$ 
           $l_{VDI}.removeXYZOccludedBy(\text{modulator}[u, v])$ 

```

---

After the previous step of the display/decomposition method is carried out, the residual **440** will mainly include view-dependent effects,  $l_{VDL}$ , which will be rendered using parallax barrier primitives as shown at **450** of FIG. 4. More specifically, the following three components will be left in the residual **440**: (1) view-dependent shading such as glossy or specular reflection; (2) scene elements that were too far away from any emissive plane to be rendered volumetrically (as shown at **430**); and (3) all occluded diffuse rays that could not be represented using a combination of emissive and modulator elements or devices of the display assembly.

Before distributing the residual light field **440** to the parallax barrier layers of the display assembly, two additional tasks may be performed by the controller/computer system. First, the depth of the specular highlights may be adjusted to be the same depth as its diffuse counterpart (otherwise, the specular highlights may not follow the projected geometry). Second, if the spacing between consecutive emissive layers is wide, some viewing rays may be undefined. With regard to error due to distant layer spacing, a continuous surface may result in holes in the result light field. These holes can be filled by analyzing the neighboring light rays that belong to the same surface and can be filled by reparameterizing and interpolating in between them. In this second case, then, the respective empty areas may be filled by performing a ray reparameterization between the light field borders that are present on the two closest emissive planes (two closest emitting devices of the display assembly).

For example, a light field may contain an empty space between two adjacent emissive layers or two emitting devices, and angular reparameterization may be used to cause the first and second emissive layers (or emitters/emitting devices) to fill the hole or empty area. Holes are filled by the automultiscopic primitives. In other words, the projection of scene objects creates holes as the parts between emissive layers (further apart than  $z_{thresh}$ ) remain unchanged. Then, the elements between layers can be scaled among the  $z$  direction until they touch the emissive layers to fill the holes. This scaling corresponds to the angular reparameterization.

The resulting light field **450** is then rendered using the light field primitives (e.g., devices within the multi-layer plenoptic display assembly) as described above. Element **460** in FIG. 4 represents what the whole display produces, e.g., emissive plus light field layer. To remove aliasing artifacts, a pre-filter

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may be applied. In contrast to a single parallax barrier light field layer, 3D scenes can be rendered more effectively with multiple parallax barriers provided at different depths. Finally, the light output from all parallax barriers can be superimposed to create an intended effect. Algorithm 4 shown below summarizes the procedure for parallax barrier rendering given a residual light field,  $l_{residue}$ , (labeled **440** in FIG. 4) and also given the diffuse component  $R_D$  and the specular/glossy components  $R_S$ .

## Algorithm 4:

---

```

 $l_{VDL} \leftarrow \text{assignViewDependentLightfield}(l_{residue}, D_{IN})$ 
for  $x, y, z, u, v, R_D, R_S \in l_{residue}$ 
  if  $R_D(x, y, z)$  on emissiveLayer
    Project  $R_S(x, y, z, u, v)$  onto  $R_S(x, y, \text{emissiveLayer}, z, u, v)$ 
  Perform hole filling for continuous surfaces: WarpResidue( $l_{residue}$ )
  for light fieldLayer  $\in D_{IN}$ 
    for  $x, y, z, u, v, R_D, R_S \in l_{residue}$ 
      light fieldLayer  $[x, y, u, v] \leftarrow R_D + R_S$ 
       $l_{VDL}.add([x, y, z, u, v, R_D, R_S])$ 

```

---

It may be useful in implementing an effective display assembly to discuss the errors that are introduced by the approximations discussed above. With regard to the emissive and blocking layers, the projection onto the planar emitters inherently produces an approximation of the motion parallax. The motion parallax produced by an object at distance  $z$  to a viewer with focal length  $f$  that moves along a baseline at a distance  $b$  can be expressed as  $d = -fb/z$ . Therefore, the relative projective approximation error of an object at distance  $z$  projected on a plane at distance  $z_0$  may be expressed by:

$$e(z, z_0) = \left| \frac{1}{z_0} - \frac{1}{z} \right|.$$

The emissive layers are, therefore, preferably placed near dense occurrences of objects in depth and the occluding layers are placed as near as possible to the respective layers that need occlusion. Furthermore, fewer display devices are needed the farther away the scene is with respect to the viewer's position. This error can be used to determine the optimal display configuration using a suited optimization method in cases where a display configuration is optimized for a given type of scene. Generally, it only depends on the depth, so different scenes with similar geometry (e.g., as in cartoons where often there is one plane background and one plane foreground) can use the same "optimal" display configuration.

With regard to the parallax barrier layers of the display assembly, parallax barrier layers trade off spatial resolution against angular resolution. Therefore, the approximation error is directly proportional to the loss in spatial resolution. However, additional errors may be introduced if aliasing occurs when the angular frequencies are too high. These problems can be overcome by either using time multiplexing for the parallax barrier display (which naturally extends its bandwidth) or by combining multiple parallax barrier displays superimposed onto the same optical path.

At this point in the description of multi-layer plenoptic display assemblies, it may be useful to analyze the bandwidth of multiple layers of parallax barrier-type displays. A Lambertian surface will correspond to a 2D plane in the 4D light field,  $l(x, y, u, v)$ . Therefore, the Fourier transform,  $l(\text{light field spectrum})$ , will include non-zero entries only on the 2D plane,  $l(\omega_x, \omega_y, s\omega_x, s\omega_y)$ , where  $s = (d - d_0)/d$ , where  $d$  corresponds to

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the distance of the surface to the  $xy$  plane, and where  $d_0$  corresponds to the distance of the  $uv$  and  $xy$  planes. As a consequence, the bandwidth of a light field display can be denoted as:

$$H(\omega_x, \omega_y, \omega_u, \omega_v) = \begin{cases} 1, & \text{for } |\omega_x| \leq \pi/\Delta_x, |\omega_y| \leq \pi/\Delta_y \\ & \text{and } |\omega_u| \leq \pi/\Delta_u, |\omega_v| \leq \pi/\Delta_v \\ 0, & \text{otherwise.} \end{cases}$$

The graph **500** of FIG. 5 shows the 2D case (not the 4D case as discussed above), and, basically, shows that any automultiscopic display may be replaced by an arbitrary number "n" of automultiscopic displays with  $1/n$  bandwidth (with two displays shown in FIG. 5 or with  $n=2$ ). The total required bandwidth of the system remains the same (e.g.,  $n$  multiplied by  $1/n$ ). A benefit is only gained in 4D, as stated below, where the total required bandwidth (e.g., the sum of all individual bandwidths) decreased by  $1/n$ . The graph **500** shows a bandwidth analysis for multiple layers of parallax barrier displays. The left part shows the bandwidth analysis for a multi-layer plenoptic display assembly with one parallax barrier. The right part, though, shows that by combining  $n$  displays the effective sampling can be reduced in two dimensions while keeping the amount of covered frequencies the same.

In case of uniform sampling in spatial and angular directions, respectively, the Nyquist limit defines the overall display bandwidth to  $a^2b^2$ , where  $a = 2\pi/\Delta_x = 2\pi/\Delta_y$  and  $b = 2\pi/\Delta_u = 2\pi/\Delta_v$ . The lengths  $a$  and  $b$  define a box that encloses all possible frequencies that can be displayed without aliasing. The maximum depth range that can be displayed without aliasing is defined by the slopes  $\pm(\Delta x/\Delta u)$  and  $\pm(\Delta y/\Delta v)$ , and these slopes then define a 3D wedge in 4D  $(\omega_x, \omega_y, \omega_u, \omega_v)$  space. This implies that only a subset of the total bandwidth can be used effectively for a given display assembly and a given frequency distribution.

When combining multiple displays, the effective bandwidth usage can be improved when displaying 4D light fields. If two light field displays are combined onto an optical path and separated by distance  $\Delta z$ , the effective sampling is sheared by  $x = x - (\Delta z/d_0)u$  and  $y = y - (\Delta z/d_0)v$ . Therefore, the light field spectrum is sheared according to:

$$\omega'_x = \omega_x$$

$$\omega'_u = \omega_u + (\Delta z/d_0)\omega_x$$

$$\omega'_y = \omega_y$$

$$\omega'_v = \omega_v + (\Delta z/d_0)\omega_y$$

This implies that the bandwidths of multiple displays are sheared with respect to each other.

The bandwidth usage for 4D light field displays can be improved when substituting one display with two displays. In this case, each of the two displays has only half of the angular sampling in both  $u$  and  $v$  directions (see, FIG. 5, for example), but it can still produce the same light field content as the single display. The overall display (or display assembly) bandwidth for two displays can then be expressed as:

$$2a^2\left(\frac{1}{2}b\right)^2 = \frac{1}{2}a^2b^2$$

By the same geometric construction, the overall bandwidth for  $n$  displays reduces to  $(1/n)a^2b^2$  while the same light field

frequency content can be displayed. This means that a system or display assembly with  $n$  displays only needs  $1/n$  bandwidth of a single display system. In cases when the frequency spectrum is sparse (e.g., when there are depth ranges that do not have any scene elements), the overall bandwidth may be optimized even further by proper positioning of the displays. This is even the case for 2D not only for 4D as described below.

Unfortunately, for 2D light fields, any general display configuration will still use the same bandwidth. However, even a multi-layered 2D parallax barrier configuration can preserve more high frequencies than a single parallax barrier display with the same bandwidth. For example, an input light field may be provided that is made up of one background object with the depth interval ( $z_{B\_MIN}$ ,  $z_{B\_MAX}$ ) and a foreground object occupying ( $z_{F\_MIN}$ ,  $z_{F\_MAX}$ ). A single parallax barrier would then have to cover the entire interval ( $z_{F\_MIN}$ ,  $z_{B\_MAX}$ ). When using multiple parallax barriers in display assemblies, the objects can be assigned to different light fields to ensure that the combined display bandwidth is allocated more efficiently. Note, the view-dependent effects should still be accurately pre-filtered in order to avoid aliasing artifacts. However, most of these can still be preserved quite well in a typical display assembly configuration. Similarly, high-frequency visibility/occlusion is preferably correctly pre-filtered to provide an aliasing-free display. Filtering is especially important for occlusions. Such occlusions look like shadows floating at the same depth as the occlude, and, as this occlude is displayed by a different automultiscopic layer out of the depth of field, the occlusion "shadow" is aliased.

With regard to quantitative error analysis, the resulting reprojection errors may be compared using a software simulation to analyze the impact of the number of emissive, modulating/blocking, and parallax barrier layers (or devices) used in a display assembly. To this end, the inventors simulated the following two different scenes: (a) a duck scene containing two objects at different depths with occlusion and (b) a sculptural bust scene depicting a continuous surface. All scenes contain a small amount of specular highlights. The simulated results were compared to a perfect rendering, and the MSE (mean squared error) between the simulated and perfect images was computed for a number of views in a field of 15 degrees. The resulting error plots 610 and 620 are shown in FIG. 6, with plot 610 showing the impact of using multiple emissive layers (or emitters/emitting devices) and plot 620 showing the impact of using multiple modulating layers (or modulators/modulating devices).

In a first step of the quantitative error analysis, the impact of an increasing number of emissive layers was analyzed. For this analysis, it was assumed that each emissive layer can be combined with a perfect occluder in order to assess the impact of the motion parallax error and specular error only. The layers were placed around the center and spaced at equidistant distances. The error plot 610 of FIG. 6 shows that the error quickly decreases when the first few layers are added. Furthermore, the plot 610 also shows that adding more than 4 emissive layers (or emitting devices) does not significantly reduce the error.

In a second step of the error analysis, the impact of occlusion errors was analyzed when a fixed number of emissive layers were used in a display assembly, and then, the analysis involved increasing the number of occlusion layers. For this analysis, the occluders or modulating layers were placed after each emissive layer, starting from a front or forward-most layer. The plot 620 of FIG. 6 shows the errors for two different emissive layer configurations. An increasing number of occluders/modulating layers helps to reduce the error significantly.

However, here the light absorption has not been considered as it highly depends on the hardware used. Current LCDs absorb around 90 percent of light such that adding too many occluders may lead to bad or lower display brightness. However, once transparent LCDs are available it will likely pay off to use more as they do absorb less light. The error plots 610, 620 also show that increasing the number of occluders leads to significantly high errors due to incorrect occlusions.

In a third step of the error analysis, the error of ray parameterization to add back occluded areas and view-dependent effects was analyzed (see plot 610 in FIG. 6). For this simulation, a perfect parallax barrier display was first used with sufficient spatial and angular resolution to display the full depth range aliasing free (see lines of plot 610 labeled as "perfect light field rendering"). Again, the analysis was performed for different numbers of emissive planes combined with one occlusion or modulating layer. In this test/experiment, a parallax barrier was used with a limited spatial resolution (e.g., barrier spacing of 6 pixels as shown by the lines/curves labeled "low resolution light field rendering"). As can be observed in the plots 610, 620, the error is quite a bit higher especially with the larger number of emissive planes.

In general, the display assemblies may be implemented with software (or code run by a CPU/processor(s)) that functions to analyze and decompose a light field to be approximated by a combination of one or more emissive layers (emitting devices) and one or more modulating layers (modulating/occluding devices). As output, the software generates the images or light field components/subsets required by each layer primitive as well as a light field describing the warped residue. The residue is then processed by a further software component of the display assembly (e.g., its controller/control computer system) to generate the images used by the automultiscopic layers. While computing the residue, the simulated views are typically computed, too. Execution time of the decomposition depends on the size of the input light field as well as the number of basic primitives used. The time, for example, may be nearly zero (or real time) in some cases when working on geometry rather than light fields as input, but the time may be greater such as varying between 30 seconds up to 3 minutes or more. Similarly, automultiscopic rendering of the residue may take up to 1 minute or more, depending on the size of the residue. The results of such processing may be stored in memory for later use in generating a 3D display with a display assembly described herein.

At this time, it may be useful to discuss exemplary devices that may be used to implement the layer primitives in embodiments of multi-layer plenoptic display assemblies. With regard to the modulator plane, common LCD monitors provide an effective way to spatially modulate light (or transparent LCDs may be used as their light transmission is much better), and LCDs may be used as the modulating device (or modulator layer/primitive) of a display assembly. Most monitors use a layer of twisted nematic (TN) liquid crystals controlled by a thin-film transistor array (TFT). These LCD monitors allow for large size, high resolution, and low crosstalk.

One disadvantage of common, commercially-available TN-LCDs is the fairly low switching speed, e.g., around 8 ms from black-to-white. There are faster switching technologies available, such as  $\pi$  cells, that can switch in 1 ms. However, this faster technology may not be as readily available at the same size and resolution as common TN-LCDs but they may be used in place of the LCDs in the display assembly embodiments. A second disadvantage is that most LCDs have a color filter layer, which attenuates a majority of the light. LCDs without this color filter tend to be manufactured for specific

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high-dynamic range applications and are much slower than their color counterparts. Due to the high light loss, it may not be practical to have more than one modulating layer per light source in a display assembly. Even with one layer, the light source should be as bright as possible. Both prototypes/em-

bodiments described below, therefore, only utilize a maximum of two TN-LCDs as the modulating devices. TN-LCDs use polarizers in front and after the LC panel and, usually, the front polarizer is coupled with an additional diffuser. In order to operate the TN-LCDs as pin-hole modulators in a display assembly, it may be useful to remove the diffusing polarizer and replace it with a clear one. Preliminary measurements showed that light transmission of the LCDs is less than 10 percent in general and around 1 percent in a full blocking state. However, it is expected that transparent LCDs may transmit up to 90 percent or more light.

With regard to the emitter plane, transparent organic light emitting diodes (OLED) screens may be a promising candidate for use as the emissive planes (or emitting devices of the display assemblies), but OLEDs are generally not yet commercially available and do not yet provide enough transparency for a practical multi-layer display prototype. Hence, the inventors used temporal multiplexing of multiple switchable diffusers in combination with a fast projector to achieve multiple stacked emissive layers. More specifically, a display assembly may include polymer-dispersed liquid crystal displays (PDLCDs) as switchable diffusers. PDLCDs are most commonly used for switchable privacy glass although they have proven useful as switchable projector screens.

PDLCDs have similar properties to TN-LCDs except that, while TN-LCDs block linearly polarized light, PDLCDs scatter arbitrarily polarized light. When driven by a square waveform, the PDLCD layers become clear and transmissive. Note, the square waveform is typically used to switch polarity of the connectors, which is used to avoid damage of the liquid crystal fluid. Switching between transparent (on) and opaque (off) is achieved by applying the square wave or no current at all. When the power is removed, the PDLCD returns to its default diffusive state. PDLCDs can be driven by a current-limited square wave to achieve high switching speeds.

A high speed projector may be used in the display assemblies to illuminate multiple PDLCDs temporally multiplexed, where the PDLCD switching is synchronized using a custom trigger circuit. Each of the PDLCDs can be switched at 60 Hz, for example, and, therefore, imposes an upper limit for the maximum frame rate achievable by time multiplexing. The PDLCD layers transmit light at approximately 80 percent and scatter some of the light, which may be negligible for most display assemblies. Note, though, the PDLCD layers remove the polarization of the incident light and, therefore, cannot be used in settings that require polarization, which is the case for all LCDs. One simple solution, though, is to add polarizers immediately in front and after each LCD.

Based on the analysis presented above, the inventors designed and implemented two types of multi-layer plenoptic displays, which are shown as display assemblies **700** and **800** in FIGS. 7 and 8. The first display assembly **700** uses spatial multiplexing to superimpose the different layers while the second display assembly **800** uses temporal multiplexing. Briefly, spatial multiplexing is performed by combining two automultiscopic displays **710** and **730** using a beam splitter **720**. Temporal multiplexing is performed in assembly **800** by combining a projector **812** with multiple emitting devices (e.g., bi-state scattering planes) **815**, **816**, **817** in an emitter assembly **814**.

As shown in FIG. 7, the display assembly **700** includes a first (or rear) parallax barrier display **710** and a second (or

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front) parallax barrier display **730**. Each display **710**, **730** is formed with a projector **712**, **732** projecting light (3D content based on light field components **760**) **713**, **733** onto the back side of an emitting device **714**, **734**. The emitting device **714**, **734** is spaced apart a small distance,  $d_{spacing}$ , from a parallel, planar modulating device **716**, **736**, which acts to block some of the light from emitting device **714**, **734** and outputs/transmits the output of the display **710**, **730** as shown at **717**, **737**.

A beam splitter (e.g., silverized glass) **720** is provided to combine these outputs **717**, **737** as shown at **740** (e.g., a portion of light **717** is transmitted and a portion of light **737** is reflected) and direct the light **740** (or output of assembly **730**) to a viewer **745** for viewing a 3D display without special glasses. The first modulating device **716** is positioned a first distance,  $d_1$ , away from the beam splitter **720** while the second modulating device **736** is positioned a second distance,  $d_2$ , away from the beam splitter **720** that is greater so as to provide two differing layers/depths of imagery to viewer **745**.

The display assembly **700** includes a controller or control computer system **750** that functions to output control signals **761**, **762** to selectively operate the two displays **710**, **730** (as discussed above with reference to FIG. 4, for example). Specifically, the system **750** includes a processor(s) **752** that runs software/code in the form of a display and/or decomposition program or routine(s) **754** that provides the functionality described above with reference particularly to Algorithms 1-4 (and, even more particularly, Algorithm 4 as there are only automultiscopic primitives). In this regard, the system **750** is shown to include memory **756** that may be used to store data/parameters necessary for performing the described decomposition and display algorithms/methods such as the design layout of the displays **710**, **730**, a threshold distance ( $z$ ) for determining whether to display on nearby emitting devices **714**, **734**, scene depth, and so on. In operation of assembly **700**, the system **750** may receive and store an input light field (or light field data set) **758**, and then use the software **754** to determine components or subsets **760** of the light field **758** to be displayed or used to operate the display devices of the displays **710**, **730** including the emitting devices **714**, **734** and the modulating devices **716**, **736**. The control signals **761**, **762** are used to cause these components **760** (as well as residuals and the like) to be displayed via operation of the projectors **712**, **732**, the emitters **714**, **734**, and the modulators **716**, **736**.

As can be seen, the display assembly **700** combines two auto-multiscopic parallax barrier displays **710**, **730** using spatial multiplexing. The parallax barriers are only used for 3D light fields, i.e., the barriers only provide distinct rays aligned with the horizontal plane. Note, 4D light fields may also be displayed with the assembly **700** by using pinholes as the barrier in place of the stripe pattern. Both displays **710**, **730** are combined onto the same optical path using a beam splitter mirror **720**. Each of the displays **710**, **730** is placed at a different distance,  $d_1$  and  $d_2$ , from the beam splitter **720**, and each display **710**, **730** is used by the control computer system **750** via signals **761**, **762** to display different parts **760** of the light field **758** to achieve increased depth range.

Each parallax barrier display **710**, **730** is composed of a projector **712**, **732** (e.g., a 120 Hz projector or the like or any emissive display device) paired with a diffuse back projection layer **714**, **734** to provide the emissive primitive and also paired with a modulating device **716**, **736** (e.g., a TN-LCD) operated to display a parallax barrier pattern to provide the modulating primitive in the assembly **700**. Parallax barrier displays usually require large spacing between the barrier stripes to achieve an acceptable angular resolution. They, therefore, produce spatially under-sample images that addi-

tionally lack a considerable amount of brightness due to the pin-hole nature of the barrier. With this in mind, the assembly 700 may employ temporal multiplexing for each barrier display 710, 730. Specifically, in one embodiment, multiple spatially offset barrier patterns are projected in short sequence with the respective light field content 760 on the emissive primitive to achieve higher perceived spatial resolution and brightness.

In one specific implementation of the display assembly 700, both projectors 712, 732 and displays 710, 730 may have a native resolution of at least about 1920×1080 with pixel spacing of approximately 0.27 mm or less. The parallax barrier 716, 736 and the emissive plane 714, 734 may be spaced apart a distance,  $d_{spacing}$ , of less than about 10 mm. The spacing between the parallax barrier slits may be between about 9 and 12 pixels for one frame and may be adjusted according to the displayed scene. Three consecutive frames were used in one implementation for temporal multiplexing, which resulted in perceived parallax barrier spacing of 3 to 4 pixels. The corresponding 9 to 12 views of each parallax barrier on modulating devices 716, 736 consequently could be used to achieve a field of view of about 7 to about 9.5 degrees. The virtual distances between the two parallax barrier displays 710, 730 was about 100 mm and about 200 mm, respectively, in one useful implementation.

FIG. 8 illustrates another display assembly 800 that uses temporal multiplexing, and it typically would include a controller to decompose an input light field and synchronize operation of the various components to achieve such temporal multiplexing (such as the computer control system 750 of FIG. 7). The assembly 800 is shown to include a projector 812 that selectively projects or outputs decomposed and/or other portions of an input light field as shown at 813. The assembly 800 then selectively uses stacked emitting devices 815, 816, 817 of an emissive assembly 814 to selectively emit these light field components, and the emitted light is then modulated with modulating device 820 to provide a display or output 821 that is visible by viewer 825 (e.g., a 3D display is perceived by an observer 825 without use of special 3D glasses). Again, the projector 812 may be replaced (or simply thought of as) any emissive device, and, in some cases, the projector 812 may take the form of a transparent OLED or the like.

In this second display assembly 800, temporal multiplexing is used. In one implementation of assembly 800, multiple switchable scattering PDLCD planes 815, 816, 817 are combined with a projector 812. These planes 815, 816, 817 are quickly switched (e.g., via control signals from a computer control system) between scattering and clear, while the synchronized projector 812 displays 813 different images on different layers 815, 816, 817. If the switching time is fast enough, these planes 815, 816, 817 appear to be both transparent and light emitting. In addition to the scattering planes 815, 816, 817, the assembly 800 includes a single modulator plane 820 at the front of the display assembly 800, and the modulator 820 performs two functions. First, it creates an auto-multiscopic display (e.g., a parallax barrier layer) with the nearest emitting plane 817. Second, it occludes desired parts of objects on all the emitting planes 815, 816, and 817.

In one particular implementation of the assembly 800, the projector 812 was chosen so as to have a native resolution of at least about 1024×768, and the modulating LCD 820 operated at a resolution of at least about 1920×1080. In this implementation, the layers 815, 816, 817 took the form of three PDLCDs that were spaced at 4 mm, 10 mm, and 16 mm from the modulating device 820. The modulating LCD 820 and the closest PDLCD 817 were used (by the controller) as

an auto-multiscopic layer to create 12 views in a 10 degree field of view, while the other PDLCDs 815, 816 were used (by the controller) as volumetric layers only.

Although the invention has been described and illustrated with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the combination and arrangement of parts can be resorted to by those skilled in the art without departing from the spirit and scope of the invention, as hereinafter claimed.

As described above, embodiments of the multi-layer plenoptic displays or display assemblies/systems of the present invention combine multiple emissive and light modulating planes (or display elements/components) to increase the depth range and resolution when compared with typical parallax barrier-type displays or volumetric displays. A multi-layer hardware prototype was fabricated and used by the inventors to test the concepts described herein. The results showed that traditional volumetric displays can be useful in showing the image content on multiple layers without the need for special glasses. However, foreground or images in planes more proximate to the viewer are additively blended indicating volumetric displays cannot properly handle occlusions (e.g., in the prototype an object in “front” of another object was additively blended rather than occluding the back/distal object). In the prototype, a modulating plane (or modulating display element or modulator) was added in front of the display, and this resolved occlusions perfectly for one view. But, it is understood that these occlusions often will not be correct for other views (e.g., provides no view-independent occlusion).

To address this issue, an exemplary multi-layer plenoptic display assembly taught herein (and built in the hardware prototype) is configured and operated to display an occlusion pattern in a plane that eliminates incorrect additive blending in a certain field of view (e.g., provided no view-dependent occlusion). Use of such a display element to display this occlusion pattern is beneficial but, without more, the display assembly may provide occlusion with many holes and incorrect occlusion cues as well. Hence, many preferred embodiments of the multi-layer plenoptic display assembly will also include and selectively operate a parallax barrier element or device (e.g., a barrier layer or plane). The parallax barrier element is operated (caused to display a particular and changeable parallax barrier) to fill in the view dependent occlusions and also to render view dependent effects such as specularities. The adding of this light field rendering provided a significant improvement over prior autostereoscopic displays including improved resolution and an enhanced depth range.

From the above discussion, it should be clear that the inventors have introduced and described multi-layered auto-multiscopic displays for 4D light fields. At this point, it may be useful to restate how this solution to providing 3D displays is achieved and its benefits. Some of this information may expand upon portions of the prior description while others (e.g., use of a lenticular sheet with a varifocal lens) will provide new and different embodiments. Briefly, the hybrid display model volumetrically combines multiple automultiscopic layers and supports horizontal and vertical parallax, a wide depth of field at large viewing angles, and nearly correct accommodation cues. Furthermore, multi-layered displays are able to use the available display bandwidth much more efficiently, e.g., see FIG. 5 and corresponding portion of this description. An efficient algorithm can be used to decompose an input light field for such multi-layered configurations. For

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synthetic scenes, an extension is proposed to existing ray tracers that supports spatial and angular anti-aliasing using super sampling.

Three physical prototype embodiments are described that implement this display model in FIGS. 7, 8, and 9. The system or prototype **700** in FIG. 7 uses two parallax-based color displays **710**, **730** that are superimposed onto the same optical path using a beam splitter **720**. In contrast, the system or prototype **900** in FIG. 9 uses a varifocal mirror, as described below in more detail, to optically replicate one integral imaging-based monochrome display onto multiple depth planes using temporal multiplexing (e.g., supporting up to about 24 layers of depth). Both prototypes are able to create multiple display layers that are superimposed additively, and each display layer is able to emit view dependent rays.

This description introduces the first hybrid display model that is able to combine the principle of translucent volumetric displays with view dependent display layers. The hybrid display model (e.g., implemented with systems **700**, **800**, and **900**) combines the advantages of volumetric and parallax-based displays. The display model can support true view dependent occlusion that previously was not possible with volumetric displays. Previous display solutions either support one layer of view dependent rays or multiple layers without view dependent rays but none have supported both. As a result, the hybrid displays of the present description are able to show a wide depth of field for horizontal and vertical parallax, large viewing angles, and nearly correct accommodation cues that have been difficult to achieve by other displays.

With further regard to FIG. 7, the display assembly **700** includes two automultiscopic layers **710**, **730** that are combined onto the same optical path using a beam splitter **720**. In one prototype the automultiscopic layers **710**, **730** are constructed using two LCD layers stacked on top of each other (rather than the projector-based arrangement shown in FIG. 7). In this embodiment, the back emissive layer includes a regular LCD display with backlight (in place of emitting device **714**, **734** and projector **712**, **732**) while the front modulating layer is formed with a disassembled and modified LCD panel from a regular LCD display (e.g., to provide modulating device **716**, **736**). Particularly, the diffusing front polarizer and the back polarizer are removed and replaced with non-diffusing and matching polarizers, rotated by 90 degrees. In order to reduce Moire patterns, an additional diffuser with a small point spread function of approximately one pixel is placed in front of the back LCD in each display **710**, **730**.

Both LCDs are then stacked on top of each other in each display layer **710**, **730** and physically separated using a layer of acrylic glass, with the panels driven, for example, by a dual-head graphics card. In the system **700**, the perceived spatial resolution may be increased by employing time multiplexing of the parallax barriers. Synchronization for one automultiscopic layer is performed implicitly such as by a graphics board or other controller **750** with control signals **761**, **762**. Synchronization between the two automultiscopic layers may use higher-end graphics boards, e.g., for controller **750**.

In FIG. 9, a volumetric display assembly **900** is shown that includes a projector **910** projecting light fields or image layers of an input light field as shown at **914** in a temporally multiplexed manner. This light **914** is modulated by a lens array assembly **920** (e.g., a micro-lens array or lenticular lens array combined with an emitting device) to provide an automultiscopic display or output **926**. The output light **928** from the lens array **920** is directed to a varifocal beam splitter **930** that is vibrated as shown at **931**. This provides a volumetric output

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display, in a viewing space of a viewer **905**, as shown with a set **950** of virtual layers **951**, **953**, **955**, **957** that are spaced parallel layers or planes of light corresponding with the outputs **926** from the lens array assembly **920**.

A controller such as control system **750** of FIG. 7 may be used to synchronize operation of the projector **910** with vibration **931** of the beam splitter **930** to selectively display portions of the input light field in each of the virtual layers **951**, **953**, **955**, **957**. Light **928** received by the beam splitter **930** is reflected **932** to a concave mirror **940**, which redirects the light **944** to the beam splitter **930** for transmission **948** to the viewer **905** in the virtual light field layers **950**.

In one prototype, a diffuser or emitting device such as a 60 Hz display is used as part of the lens array **920** to receive the light from the projector **910** (e.g., the projector **910** may be a high-speed DLP projector used as a back light). The depth extrusion was achieved using a large vibrating beam splitter **930**, which may take the form of a metalized Mylar polyester film membrane stretched over a circular hoop. Three or more equidistant transducers, in one implementation, were mounted to the edge of the hoop in order to axially vibrate the beam splitter **930**. The beam splitter's surface tension was tuned so as to vibrate **931** the beam splitter **930** at an eigenfrequency of about 30 Hz with a high Q-factor, and, as such, its surface was alternatively convex and concave.

In this manner, the display light or surface **928**, **932** is relayed by the beam splitter **930** towards a fixed concave mirror **940**. The returning light **944** passes through the beam splitter **930** as shown at **948** and forms a real 2.5D stack **950** of spaced apart 2D images **951**, **953**, **955**, **957** (2 to 24 or more with 4 layers/planes shown in FIG. 9) in front of the display assembly **900**. In one particular implementation, the display assembly **900** was operated to create a layered volume **950** with dimensions of 16.7 cm by 12.5 cm by 18.8 cm.

In the assembly **900**, the lens array assembly **920** may include an LCD with a rear-projected emissive screen with a micro-lens array placed on top. The display **900** is able to support volumetric layers **950** with occlusion effects. A high-speed DLP projector **910** can be used in the assembly **900** to provide monochrome images that are synchronized to the vibration **931** of the mirror **930**. Using the projector's monochrome mode, the assembly **900** is able to provide up to 24 images per stroke of the mirror **930** at an aggregate frame rate of 1440 frames per second, forming up to 24 image planes for set **950** at 60 Hz.

The microlens array may be a lenticular sheet or may include staggered 2D fly's eye lenslets in a close-packed hexagonal format in order to support both horizontal and vertical ray separation of the underlying image **914**. The projector's image size (e.g., at a resolution of 1024x768 pixels) may be chosen to provide 13 pixels horizontally and 11.3 pixels vertically under each lenslet of the array **920** in this latter embodiment. The field of view of the lenslets (e.g., 41 degrees) exceeds the field of view of the volumetric display (e.g., 19 degrees) provided by varifocal beam splitter **930**. Therefore in one embodiment, the outer viewing rays may be padded to reduce light transmission through the seams between the individual lenses, which can lead to effects similar to cross talk. In one specific but not limiting case, a total number of 6x6 rays were used per lenslet.

The display assembly **900** and assemblies **700** and **800** are examples of multi-layered automultiscopic displays for 4D light fields. The assemblies **700**, **800**, and **900** volumetrically combine multiple automultiscopic layers and support horizontal and vertical parallax and further support better accommodation cues than single layer elements.

Significantly, multi-layered displays such as assemblies **700, 800, and 900** are able to use the available display bandwidth more efficiently. The combined bandwidth of  $n$  layers only requires  $1/n$  of the total ray count of a single layer display to show the same diffuse scene content with approximated occlusions. In other words, the substitution of one layer with bandwidth  $B$  by  $n$  layers requires a total bandwidth of only  $B/n$  to cover the same spectra, and each layer has a bandwidth of only  $B/(n \cdot n)$ . An efficient algorithm (as described herein) can be used to decompose an input light field for such multi-layered configurations.

In review, the multi-layered automultiscopic displays may be thought of as implementing a hybrid display model that combines the benefits of volumetric and parallax-based displays. For example, multiple translucent display layers at different depths are combined onto the same optical path. In contrast to previous volumetric displays, each of the layers includes an automultiscopic layer to emit true view dependent rays such that the display assembly is capable of view-dependent occlusion.

FIG. 10 illustrates with schematic diagram **1000** this concept for a dual-layer configuration (the diagram **1000** shows a multi-layered automultiscopic display for 4D light fields), but, it should be remembered that any number of layers (2 or more) is possible and useful as in many applications the more layers used the better the bandwidth gain. Each layer includes an automultiscopic display, e.g., using parallax barriers (as shown) or lens arrays. The layers are multiplexed on the same optical path.

Rays are generated on an emissive back plane with angular sampling  $(\Delta u, \Delta v)$ . The emissive pixels are spatially separated into view-dependent rays on the modulating plane, e.g., using pinholes on the modulating front plane with spatial sampling  $(\Delta x, \Delta y)$ . The emissive and modulating planes of each layer are separated by a distance,  $d_0$ , and the layers themselves are positioned apart at a distance,  $Z_D$ . The individual automultiscopic layers are then superimposed onto the same optical path at different depths. An assumption is made that the layers do not support true occlusion, i.e., a display layer does not block light from any back layer.

As discussed above with reference to FIG. 5, bandwidth analysis can be performed for multi-layered automultiscopic displays (e.g., illustrated as a 2D cut through the 4D light field) by comparing a single layer display and a dual layer configuration (such as shown at **1000** in FIG. 10). While both display configurations share the same spatial resolution, each layer in the dual configuration only requires one fourth angular resolution for horizontal and vertical parallax (e.g., angular sampling is reduced by one half in both the  $u$  and the  $v$  direction for both display layers). As a consequence, two layers can display the same diffuse scene content compared to a single layer but using only half the number of rays. Hence, the overall bandwidth and ray count for  $n$  display layers reduces to  $1/n$  compared to a single layer configuration. Both displays exhibit the same depth of field for frequencies at full spatial resolution.

Regarding a useful software framework, one prototype implemented the above teaching/methods for a light field distribution algorithm for ray tracking with a framework for general purpose ray tracking on a GPU. The implementation performs ray tracking for all layers in parallel, and all rays are generated according to the ray sampling of the layers. Anti-aliasing is achieved by stochastic super-sampling around the original sampling locations, and all samples are interpolated using a box filter as one exemplary filter but other signal filters may be used (e.g., a Gaussian filter, a sinc filter, a Lanczos

filter, and the like). The ray tracer supports basic ray casting but could readily be extended for more realistic image generation.

Regarding layer borders, the layer distribution can introduce high frequencies, especially when continuous surfaces are separated by two layers. In order to avoid noisy artifacts, a high number of multi-samples may be desirable. To mitigate this issue, instead of using binary cuts, one implementation uses "fuzzy" layer borders, e.g., slightly overlap neighboring depth of fields and linearly weight the corresponding samples that fall within the overlapping region, with respect to the actual layer borders. This strategy can greatly reduce noisy artifacts without the need for very high sampling densities.

Regarding optimizing field of view, many rays will fall outside the field of view for close viewing positions when using regular sampling. In order to increase the effective ray utilization for a given viewing position, the emitted view rays can be sheared along the angular direction  $u' = u + sx$  and  $v' = v + sy$ , where  $s$  is dependent on the display parameters and viewing distance. In one implementation, the sheared rays are rounded to the nearest sampling location determined by the pixel grid.

With regard to display simulations, simulated results were generated using a custom ray tracer implemented within a general ray tracing framework for use with a GPU (such as the OptiX Ray Tracing Engine provided by NVIDIA Corporation or the like). Each display layer was represented by two planes. The emitting plane was assigned a luminance texture corresponding to the generated pattern from the light field distribution. The modulating plane was assigned a transmission texture corresponding to the spatial sampling. For the simulation, super-sampling of the viewing rays was applied to approximate cross-talk.

We claim:

1. An automultiscopic display apparatus, comprising:
  - a first parallax barrier or lens system selectively operable to display parallax barrier patterns;
  - a first planar emitting device selectively operable to emit light to the first parallax barrier or lens system;
  - a second parallax barrier or lens system selectively operable to display parallax barrier patterns;
  - a second planar emitting device selectively operable to emit light to the second parallax barrier or lens system;
  - a beam splitter positioned between the first and second parallax barrier or lens systems to receive output light from the first and second parallax barrier or lens systems on first and second surfaces of the beam splitter, respectively; and
  - a controller operating the first planar emitting devices to display a first component of a light field and the second planar emitting device to display a second component of the light field,

wherein the first parallax barrier or lens system is spaced apart from the first surface of the beam splitter a first distance and the second parallax barrier or lens system is spaced apart from the second surface of the beam splitter a second distance greater than the first distance, whereby the first and second components are displayed in spaced apart planes.

2. The apparatus of claim 1, wherein the controller operates the first and second parallax barrier or lens systems to occlude portions of the light field whereby the output light provided to the beam splitter comprises an automultiscopic display.

3. The apparatus of claim 1, wherein the first and second emitting devices each comprises an array of point light sources programmable by the controller to selectively display the first and second components of the light field.

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4. The apparatus of claim 3, wherein the first and second emitting devices each comprise liquid crystal display (LCD) monitors.

5. The apparatus of claim 3, wherein the first and second components comprise view independent components extracted from the light field.

6. The apparatus of claim 5, wherein the first component includes view-dependent components extracted from the light field and the parallax barrier pattern is generated to mask view-dependent occlusions in the light field, whereby portions of the first component are blocked by the first parallax barrier or lens system.

7. The apparatus of claim 1, wherein the first and second parallax barrier or lens systems are configured to be opaque or transparent at an array of spatial positions to display the parallax barrier patterns.

8. The apparatus of claim 7, wherein the first and second parallax barrier or lens systems each comprises an LCD monitor.

9. An automultiscopic display apparatus, comprising:

a first parallax barrier or lens system selectively operable to display parallax barrier patterns;

a first planar emitting device selectively operable to emit light to the first parallax barrier or lens system;

a second parallax barrier or lens system selectively operable to display parallax barrier patterns;

a second planar emitting device selectively operable to emit light to the second parallax barrier or lens system;

a beam splitter positioned between the first and second parallax barrier or lens systems to receive output light from the first and second parallax barrier or lens systems on first and second surfaces of the beam splitter, respectively; and

a controller operating the first planar emitting device to display a first component of a light field and the second planar emitting device to display a second component of the light field,

wherein the first and second components of the light field correspond to images at first and second depths within the light field, and

wherein the first and second components comprise view independent components extracted from the light field.

10. The apparatus of claim 9, wherein the controller operates the first and second parallax barrier or lens systems to occlude portions of the light field whereby the output light provided to the beam splitter comprises an automultiscopic display.

11. The apparatus of claim 9, wherein the first parallax barrier or lens system is spaced apart from the first surface of the beam splitter a first distance and the second parallax barrier or lens system is spaced apart from the second surface of the beam splitter a second distance greater than the first distance.

12. The apparatus of claim 9, wherein the first and second emitting devices each comprises an array of point light

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sources programmable by the controller to selectively display the first and second components of the light field.

13. The apparatus of claim 12, wherein the first and second emitting devices each comprise liquid crystal display (LCD) monitors.

14. The apparatus of claim 12, wherein the first and second emitting devices are positioned to display the first and second components in spaced apart planes.

15. The apparatus of claim 14, wherein the first component includes view-dependent components extracted from the light field and the parallax barrier pattern is generated to mask view-dependent occlusions in the light field, whereby portions of the first component are blocked by the first parallax barrier or lens system.

16. The apparatus of claim 9, wherein the first and second parallax barrier or lens systems are configured to be opaque or transparent at an array of spatial positions to display the parallax barrier patterns.

17. The apparatus of claim 16, wherein the first and second parallax barrier or lens systems each comprises an LCD monitor.

18. An automultiscopic display apparatus, comprising:

a first parallax barrier or lens system selectively operable to display parallax barrier patterns;

a first planar emitting device selectively operable to emit light to the first parallax barrier or lens system;

a second parallax barrier or lens system selectively operable to display parallax barrier patterns;

a second planar emitting device selectively operable to emit light to the second parallax barrier or lens system;

a beam splitter positioned between the first and second parallax barrier or lens systems to receive output light from the first and second parallax barrier or lens systems on first and second surfaces of the beam splitter, respectively; and

a controller operating the first planar emitting device to display a first component of a light field and the second planar emitting device to display a second component of the light field,

wherein the first component includes view-dependent components extracted from the light field and the parallax barrier pattern is generated to mask view-dependent occlusions in the light field, whereby portions of the first component are blocked by the first parallax barrier or lens system.

19. The apparatus of claim 18, wherein the first parallax barrier or lens system is spaced apart from the first surface of the beam splitter a first distance and the second parallax barrier or lens system is spaced apart from the second surface of the beam splitter a second distance greater than the first distance and wherein the first and second emitting devices each comprises an array of point light sources programmable by the controller to selectively display the first and second components of the light field.

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